SYSTEM CONSIDERATIONS CONCERNING THE DEVELOPMENT OF HIGH EFFICIENCY CERAMIC ARMORS

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Ceramic materials have seen increasing use in ballistic applications where a combination of high compressive strength and low density are important. This very high compressive strength of ceramic materials offers the potential for more efficient destruction of penetrators then more conventional monolithic metals. However, the extreme localized loading of the ceramic during a ballistic impact typically generates early failure and comminution of these brittle materials, and subsequent considerable loss of ballistic efficiency. Consequently, these tiles are usually employed in an *armor system* where backing and surround plates are utilized in an attempt to increase efficiency of the comminuted ceramic. These attempts at backing or surrounding the ceramic with various materials have met with mixed success, partly because the underlying principals which influence successful system design are not clearly understood. Recently, work at the ARL has shown that the type of system confinement or encapsulation can influence the ballistic efficiency of the ceramic tile, and that "dwell" type defeat of penetrators can be achieved on ceramic front surfaces. Various factors (backing plate stiffness, ceramic compressive strength, ceramic/encapsulation impendance mismatch, etc.) have been shown to be important contributors to the overall efficiency of the ceramic/confinement system. This paper will present a investigation of these important design parameters that influence ceramic armor system efficiency, and will provide specific design equations, and experimental evidence for armor system development.

INTRODUCTION

Extremely lightweight armors for defeat of armor piercing (AP) threats (7.62 mm through 50 mm) have typically been two part armor systems consisting of a hard ceramic facing (typically Boron Carbide, Silicon Carbide, or Aluminum Oxide), glued to a structural backing plate of metal or composite material [Florence, Defourneaux]. These armor systems function efficiently by breakup of the AP threat in the ceramic, with termination of fragment energy in the backing material. It was postulated that the performance of these "composite" armor systems was influenced by the ability of the ceramic to shatter and destroy some portion of the AP threat on the tile surface, with some harder ceramics being considerably more effective armor components. However, recent investigations [Hauver, Bruchey and Horwath] have demonstrated that the penetration resistance of ceramic materials (ability to shatter a threat) is influenced not only by: 1) the ceramic hardness or compressive strength; but also by; 2) the type of confinement or encapsulation which surrounds the ceramic tile.

With respect to the ceramic tile hardness, ballistic tests by various researchers (Rozenberg and Yeshurun, Sternberg) have shown that the performance of ceramic type armor materials are a function of material strength / hardness (typical static compression strengths of 3 - 7 GPa. and hardnesses of 2000 - 3000 kg/mm^2 for various ceramics). In experiments where *"interface defeat" or "dwell"* type mechanisms are responsible for penetrator destruction, the strength and/or hardness of the ceramic material is especially important.

Regarding the encapsulation of ceramic tiles, Abkowitz, Weihrauch, Abkowitz, Mariano, and Papetti investigated several types of HIP encapsulation of ceramic tiles, and demonstrated increased multi-hit performance associated with this type of confinement. Bless, Benyami, Apgar, and Eylon postulated that ceramic tile impenetrability is influenced by good ceramic tile confinement, and proper faceplate construction to allow formation of a hydrostatic cushion, and suppression of tensile failure of the ceramic. Hauver and others have shown excellent performance of ceramic tiles that are heavily confined. Bruchey and Horwath have shown that SiC tiles encapsulated by a Hot Isostatically Pressed (HIP'd) titanium alloy have noteworthy increases in mass efficiency when compared to standard Depth-of-Penetration (DOP) configuration tiles. For HIP ceramic configurations (see Figure 1) impacted by tungsten alloy rods (Bruchey and Horwath), ceramic tile efficiencies have been doubled. These HIP tile armor systems function efficiently by the complete destruction of the penetrator on the ceramic tile surface, an enhancement of the breakup and shatter mechanisms typically employed in ceramic light armor systems.

The design of armor tile systems, as discussed above, for complete destruction of AP penetrator threats on the ceramic front surface is a complex undertaking, but can be achieved if several key constraints concerning the loading of the ceramic/tile are not exceeded. These constraints, related to the stress state in the ceramic/surround structure, are discussed below in a development of some equations governing the design of ceramic armor systems.

ARMOR SYSTEM DESIGN

The design of an efficient ceramic system begins by considering the mechanisms by which a ceramic tile fails during loading, and designing the armor system to reduce the stresses contributing to early failure of the ceramic tile. Consideration of the ballistic event (with emphasis on penetrator interface defeat on ceramic front surface as depicted in Figure 1 below) leads to the determination that two primary areas of concern are: *1) the compressional loading of the ceramic directly under the penetrator rod, and, 2) the maximum flexure of the ceramic plate and tensile stress/strain at the plate rear surface.*

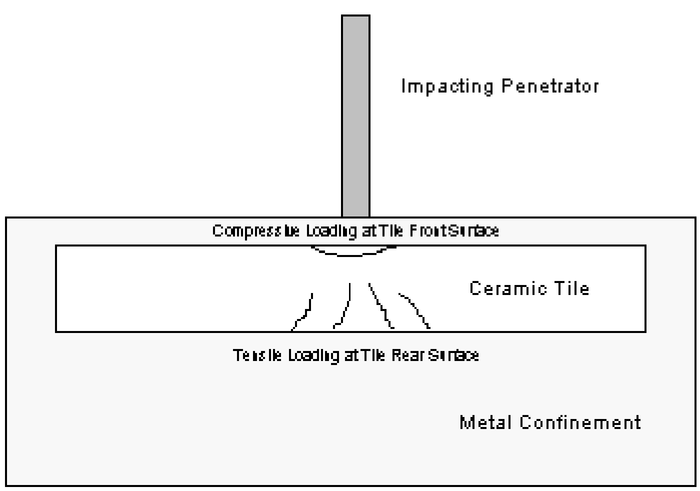

Figure 1. Tile Schematic and Loading During Ballistic Event.

Development of fractured ceramic as a result of the above two mechanisms considerably reduces the ceramic ballistic efficiency, and may abruptly stop the interface defeat mechanisms as described by Hauver. Consequently, equations concerning the events described above were developed and incorporated into computer algorithms for tile system design.

PRELIMINARY DESIGN CALCULATIONS

These algorithms involve a series of calculations concerning many parameters of the penetrator and armor system, with the primary goal of the calculations being the design of a complete armor system which minimizes: 1) compressional overload of the tile, or, 2) flexural failure of the ceramic tile in tension at the rear surface. Calculated quantities which are employed in the tile design equations include:

Penetrator "strength" per Tate model - Y_p .

Here the dynamic yield strength σ_{yp} for the penetrator material is first calculated based on the following equation of state after Johnson and Cook:

$$\sigma_{yp} = A + (B * (\square_f)^n) * [1 + C * Log(Vel/Length)] * (1 - \frac{T - T_{room}}{T_{melt} - T_{room}})$$

where for a typical 93% tungsten alloy,

A = 1505.8, B= 176.5, C= 0.0016, n=.12, T_{room} = 300, T_{melt} = 1700, T= 800

and then after Tate, the effective penetrator material "strength" Y_p is,

$Y_p = 1.7 * \sigma_{yp}$.

Penetrator strain to failure from Johnson Cook equation of state - ε_f

New "mushroomed" penetrator presented area - A_1

Utilizing the Johnson-Cook equation of state, the penetrator strain to failure can be calculated to determine the total area of the ceramic tile that is loaded by the mushroomed head of the penetrator.

$$\varepsilon_f = (D_1 + D_2 \exp D_3\sigma^*)(1 + D_4 \ln \dot{\varepsilon}^*)(1 + D_5 T^*)$$

where for 93% tungsten alloy,

D_1= 0.0, D_2= 0.33, D_3= -1.5, D_4= 0.042, D_5 = 0.0

and the presented area is then,

$$A_1 = \frac{[(Dia_o * \varepsilon_f) + Dia_o]^2 \pi}{4}$$

Dynamic yield strength of ceramic - σ_{yt}

Established equations for calculation of the dynamic yield strength from hugoniot elastic limit (HEL) data were utilized as below:

$$\sigma_{yt} = HEL * [\frac{1-2\nu}{1-\nu}];$$ ν = poisson's ratio for ceramic (.16 for SiC)

Ceramic "strength" per Tate model - R_t.

Utilizing the ceramic dynamic yield strength calculated above, a ceramic "strength" can be estimated using the method of Tate (empirical fit to data), and takes the form:

$$R_t = \sigma_{yt}(.667+\ln\frac{1.14E_t}{2\sigma_{yt}});$$ E_t = Young's Modulus of ceramic

"Interface" velocity in front plate material after Tate - U_i.

A simplified approach to determining the interface velocity U_i of the penetrator in the front plate assumes hydrodynamic flow and analysis after Tate. This interface velocity is close to the velocity of the penetrator that the ceramic plate experiences on impact. Thicker front plates will lower the interface velocity, and consequently the load on the ceramic is reduced. After Tate, and neglecting non-steady state conditions, the following equations are utilized to predict the interface velocity in the front plate:

$$\mu = \sqrt{\frac{\rho_{plate}}{\rho_{pen}}}; \qquad A = \frac{(2*(R_t - Y_p)(1-\mu^2)}{\rho_{plate}}; \qquad U = \frac{V_o - \mu\sqrt{V_o^2 + A}}{(1-\mu^2)}$$

where,

ρ_{plate} = plate density; ρ_{pen} = penetrator density; V_o = initial penetrator velocity

Stress at ceramic tile front surface after Encapsulation - σ_{hip}.

The stresses generated in the ceramic tile after the encapsulation processing (cooling of HIP sandwich) can be quite severe. The stress state depends on the relative thickness of the ceramic tile, the thickness of front and rear plates, and, the thermal expansion coefficient differential. Typically, with a thin front plate, and backing plate thickness that is larger then the ceramic tile thickness, a state of tensile stress in the ceramic tile front surface may result. The actual stress is calculated after Hsueh and Evans as below.

$$\sigma_{cer} = E_c(\varepsilon_o + (\alpha_m - \alpha_c)\delta T) + E_c(x - t_n)/r$$

using,

$$t_n = \frac{E_c t_c^2 - E_m t_m^2}{2(E_m t_m + E_c t_c)}, \qquad \varepsilon_o = \frac{E_c(\alpha_c - \alpha_m)\delta T t_c}{E_m t_m + E_c t_c},$$

$$\frac{1}{r} = \frac{6E_m E_c t_m t_c(t_m + t_c)(\alpha_c - \alpha_m)\delta T}{E_m^2 t_m^4 + E_c^2 t_m^4 + 2E_m E_c t_m t_c(2t_m^2 + 2t_c^2 + 3t_m t_c)},$$

where;

E_m, E_c = Backing and ceramic material modulii, respectively
t_m, t_c = Thickness of backing material and ceramic material, respectively
α_m, α_c = Thermal expansion coefficient of backing material and ceramic
δT = Temperature differential on cool down from HIP temperature
x = ceramic half thickness

Allowed deflection of ceramic tile - δ_{cer}.

The deflection of the ceramic tile that is possible is calculated utilizing the three-point -bend data for the particular ceramic material in combination with design equations from Roark's handbook.

The load P required to rupture the ceramic (rupture stress in outer fibers under load determined in three point bend test) is determined after equations developed by Roark. This load is then input to the deflection (δ_{cer}) equation to determine the maximum deflection possible at load. The development of the current equations does not attempt to rationalize the change in stress state which occurs during the bending of a plate, as compared to the long and narrow three-point bend specimen. The deflection is then:

$$\delta_{cer} = P \Big/ \left(8 * K * L_e^{\,2}\right)$$

where

$$L_e^{\,2} = \frac{E_{cer} * t_c^{\,3}}{\left[12 * K * (1-\upsilon^2)\right]^{.25}}; \qquad P = \frac{2 * \sigma_{rup} * \pi * t_c^{\,2}}{3*(1+\upsilon)[\ln(\frac{L_e}{r_{pen}}) + .6159]}$$

$K = (w / A_l) / \delta$; "spring constant" or modulus for foundation

σ_{rup} = Rupture stress from three point bend test

DWELL (Interface Defeat) CHECK FOR CERAMIC CONFIGURATIONS

The above sections were concerned with the development of the equations necessary for preliminary calculations regarding the ballistic loading of the HIP tile assembly. These preliminary calculations are necessary to determine the compressional stresses on the ceramic surface, as well as the deflection and tensile strain in the ceramic back surface. If the tile is not overloaded in compression under the penetrator, and/or, if the tensile bending at the rear surface does not exceed rupture levels, interface defeat of the round may occur at the tile front surface. Then, determination of ceramic tile ballistic performance ultimately depends on the micro-cracking damage developed during overloading and bending, and the following calculations assist in determining the extent of tile fracture, with subsequent implications for tile resistance to penetration.

1. Compressional Loading Under Penetrator - σ_p, and Load on ceramic tile - L_p.

The development of equations concerning the pressures generated during impact events has been treated by several individuals and summarized in Meyers. The analysis assumes a simple Mie-Gruniesen form for the equation of state utilizing two terms, and an initial momentum balance. From particle velocity equations, it can be shown that the pressure, P_1, at the rod/ceramic interface is given by:

$$V - U_{p1} = U_{p2,} \qquad (1)$$

where U_p and U_s are particle and shock velocities, while momentum balance and equations of state may be expressed as below.

For penetrator: $P_1 = \rho_1 U_{s1} U_{p1}$; and $\qquad U_{s1} = C_1 + S_1 U_{p1}$

For the target: $P_2 = \rho_2 U_{s2} U_{p2}$; and $\qquad U_{s2} = C_2 + S_2 U_{p2}$

substituting the EOS equations into the momentum equations yields:

$$P_1 = \rho_1(C_1 + S_1U_{p1})\, U_{p1} \quad (2); \qquad P_2 = \rho_2(C_2 + S_2U_{p2})\, U_{p2} \quad (3)$$

utilizing (1) in (2) yields:

$$P_1 = \rho_1 C_1(V - U_{p2}) + \rho_1 S_1(V - U_{p2})^2 \qquad (4)$$

Then utilizing (3) and (4) since $P_1 = P_2$, gives a quadratic to solve for U_{p2}

$$U^2_{p2}(\rho_2 S_2 - \rho_1 S_1) + U_{p2}(\rho_2 C_2 + \rho_1 C_1 + 2\rho_1 S_1 V) - \rho_1(C_1 V + S_1 V^2) = 0$$

The pressure can then be found from (2) above utilizing U_{p2}. In the above development the following variables were utilized,

P_1, P_2	= pressures in penetrator and ceramic target
ρ_1, ρ_2	= densities of penetrator and ceramic target
V	= initial penetrator velocity

The resultant pressure is reduced at tile obliquity, and the component of the pressure in the tile thickness direction is employed in the calculations as below:

$$P_1 = P_1 * \cos(\text{Obliquity of tile})$$

Equation (3) can be solved for the ceramic target particle velocity (U_{p2}), which is utilized in equation (2) to determine the pressure at the ceramic/penetrator interface (pressure under the penetrator). This pressure of the ballistic event can be compared to the high strain rate "strength" of the ceramic calculated based on the dynamic yield of the ceramic, and "Tate" estimate of Rt for the material. These comparisons lead to a qualitative understanding concerning compressional overloading of the ceramic material, which can be utilized in further analysis of the ballistic performance of the ceramic.

2. Flexure of Ceramic Tile Under Ballistic Load

The equations for modeling the ceramic flexure under load have been developed by Roark and others, and are utilized with only slight modification. The calculated deflection under the ballistic load is compared to the allowed deflection in three-point bending, and impact on "dwell" type defeat mechanisms, and ceramic efficiency is determined. The Deflection (Δ_{cer}) of the ceramic tile is again calculated per Roark (sixth edition, page 473), where loading of square tile is over circle of certain radius, while tile is supported by an elastic foundation. First a foundation "modulus" is calculated utilizing the load to generate a certain deflection in the plate, assuming loading only over the "mushroomed penetrator area.

$$w = \frac{\delta * E_b * t_b^{\,3}}{.1267 * b^2}$$

And then the back plate "modulus" or spring constant, K, (GPa per meter deflection) can be found as before from:

$$K = (w \,/\, A_l) \,/\, \delta$$

Then the ceramic deflection is determined from Roark's equations utilizing the elastic foundation concept, and the ballistic load P from the penetrator, as below:

$$\Delta_{cer} = P \Big/ \left(8 * K * L_e^{\,2}\right); \quad \text{with} \quad L_e^{\,2} = \frac{E_{cer} * t_c^{\,3}}{\left[12 * K * (1 - \nu^2)\right]^{.25}}$$

BALLISTIC RESULT CALCULATION

Finally, ballistic performance can be calculated utilizing mass efficiencies determined during ballistic test of several encapsulated ceramic (HIP) modules. The mass efficiency (e_m) of the tiles is degraded as the pressure of contact P_1 on the tile exceeds the R_t "strength" of the ceramic, and as the tile flexure Δ_{cer} continues beyond the elastic limit strain of the ceramic plate. The reduction in efficiency is simply:

e_m (ceramic) $= e_m$ * (Rupture Strength / P_1) * (δ_{cer}/ Δ_{cer})
Where, for example, the starting efficiency (e_m) for SiC is 9.5, and is degraded to 4.75 for considerable fracture and comminution of the ceramic. For the Ti-6AL-4V confinement around the ceramic tile, the em is assumed to be a constant 1.6 over the velocity range of interest (after Burkins et. al). Then the RHA penetration performance, P/L (at velocity), for typical tungsten alloy rods of various L/D can be estimated utilizing the following equation, from Farrand.

P/L = 2.242 * Exp(-(1440 / Velocity) ^ 2)

From the above sets of equations, after conversion of the tile components to RHA equivalent thickness (Ti-6Al-4V and ceramic) the ballistic performance of the module can be calculated. The ballistic performance of each armor design can then be estimated for a particular penetrator.

EXAMPLE OF PREDICTIONS AND COMPARISON WITH BALLISTIC DATA

Various HIP tile configurations (where surround of metal is hot isostatic pressed around ceramic) have been tested at ARL by these authors. The performance of these tiles is presented in Figure 1. The performance of these several armor systems containing ceramic materials in HIP configurations was also estimated utilizing the methods/equations described above. As indicated in the figure, the code is capable of determining the relative extent to which a particular tile geometry achieves "dwell" against a type of threat, and subsequently, a fairly good estimate of tile performance results.

Threat 1 = 65 gram, L/D = 10, 93% tungsten alloy rod. A = 1300 m/s; B = 1500 m/s
Threat 2 = 550 gram, L/D = 5, 93% tungsten alloy rod. 1600 m/s
Threat 3 = 70 gram, L/D = 5, 93% tungsten alloy rod. 1600 m/s

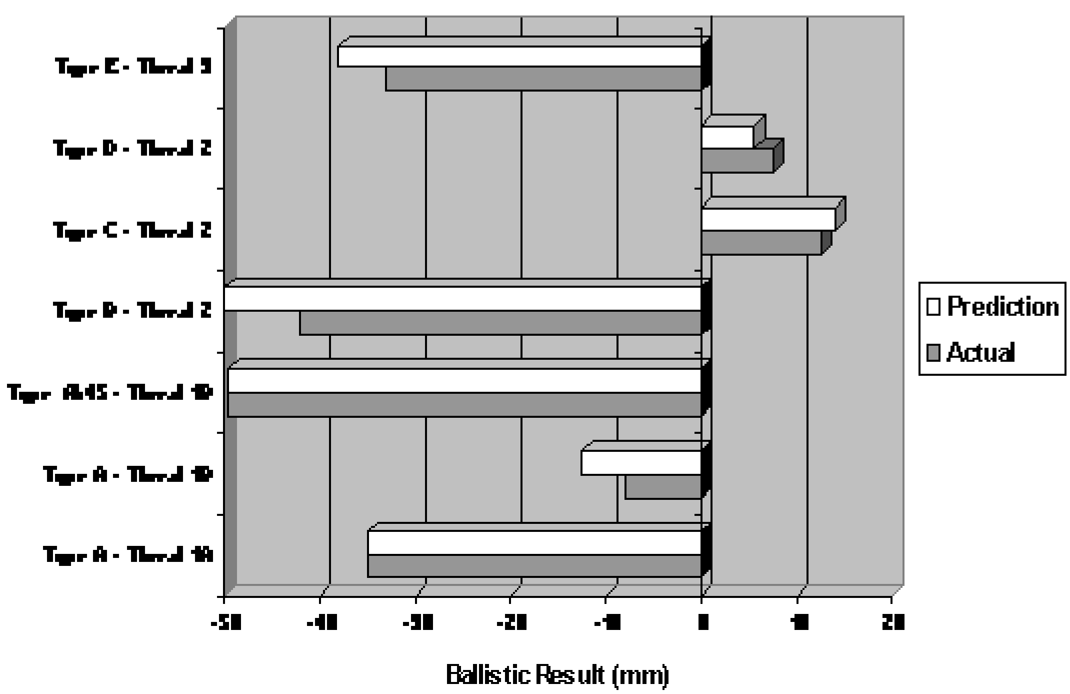

Figure 2. Comparison of Ballistic Data with Model Predictions

For Type A targets the design was: 6 mm Ti-6Al-4V / 12.7 mm SiC / 35 mm Ti-6Al-4V
For Type B targets the design was: 25 mm Ti-6Al-4V / 50 mm SiC / 50 mm Ti-6Al-4V
For Type C targets the design was: 25 mm Ti-6Al-4V / 25 mm SiC / 75 mm Ti-6Al-4V
For Type D targets the design was: 12.7 mm Ti-6Al-4V / 37.5 mm SiC / 75 mm Ti-6Al-4V
For Type E targets the design was: 6 mm Ti-6Al-4V / 19 mm SiC / 38 mm Ti-6Al-4V

CONCLUSIONS

A model for ceramic containing armor systems has been proposed which utilizes plate bending analysis and materials equations-of-state to determine if "dwell" type defeat of penetrators can be achieved for particular penetrator and target combinations. Ballistic performance of a particular target can be estimated utilizing these equations, and experimental evidence and predicted data show good agreement.

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